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Improving the Accessibility of Urban Transportation Networks for People with Disabilities

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Abstract

What is the most effective way to enhance the accessibility of our oldest and largest public transportation systems for people with reduced mobility? The intersection of limits to government support with the growing mobility needs of the elderly and of people with disabilities calls for the development of tools that enable us to better prioritise investment in those areas that would deliver the greatest benefits to travellers. In principle and, to a lesser extent, in practice, many trains and buses are already accessible to nearly all users, leaving the stations and interchanges as the single largest and most expensive challenge facing operators trying to improve overall access to the network.

Focussing on travel time and interchange differences, we present a method that uses network science and spatio-temporal analysis to rank stations in a way that minimizes the divergence between accessible and non-accessible routes. Taking London as case study, we show that 50% of the most frequently followed journeys become 50% longer when wheelchair accessibility becomes a constraint. Prioritising accessibility upgrades using our network approach yields a total travel time that is more than 8 times better than a solution based on random choice, and 30% more effective than a solution that seeks solely to minimise the number of interchanges facing those with mobility constraints. These results highlight the potential for the analysis of ‘smart card’ data to enable network operators to obtain maximum value from their infrastructure investments in support of expanded access to all users.

Keywords: Accessibility, Inclusive Transport, Multimodal Transport

1. Introduction

The spread of cheap, low-power sensors on our person and throughout our environment is enabling a new class of 'smarter city' to emerge in which the digital traces left by the movement and interaction of individuals and objects can be collected and analysed to improve the number and resilience of services available to residents. Data from devices such as mobile phones have been used to study a range of phenomena, including: how the movement of people affects the spread of viruses [1, 2]; how knowledge of individual journeys can be used to encourage car sharing [3]; how mobile phones can be used to characterise urban activity [4] and the impact of social events [5]; and how mobility data can help network operators to optimize urban transportation networks [6, 7, 8].

More recently, public transport smart card data has been used to study travel behaviour with a particular focus on travel time [9], Origin/Destination matrices [10], and the prediction of journey time and destination [11] with the aim of providing personalised routing recommendations [12, 13]. However, to the best of our knowledge, this type of data has not been used to examine the accessibility of a public transport network as *whole* for people with disabilities. So we here contrast the purpose of our research with those approaches – such as personalized route planning for people with physical impairments [14] and machine-learning techniques to support navigation by disabled people [15] – designed to support *individual* mobility.

Previous work on disabled access to public transport has relied solely on survey data (e.g. [16]), but the importance of accessible transport can be gauged from the abundant work on existing need (e.g. [17, 18, 19]), as well as the emergence of policy specifically designed to expand and improve access (see, for example, the European Policy on Urban Transport[1]). Consequently, we feel that it is important to consider whether a system exists that would enable us to measure and identify the potential improvements that maximise benefits to disabled users as a group. In other words, if we were in a position to selectively upgrade parts of the network, then which stations would enable us to realise the greatest benefits for accessibility and accessible travel times?

[1] `http://www.eukn.org`.

Materials and Methods

Study Area

We focused our case study on metropolitan London since the city has a particularly large public transport network consisting of no less than seven discrete systems: underground rail (the Underground, also known as the Tube), aboveground rail (the Overground), light rail (the Docklands Light Railway, or DLR for short), trams, boats, busses, and suburban and intercity rail. All buses in regular use are low-floor vehicles that are technically accessible to wheelchair users, and these users also have boarding priority. For the rail system – Underground, Overground, Tramlink, and DLR – the picture is more mixed: at the time of our research there were 64 accessible stations[2]. Unfortunately, step-free access to platforms does not mean that a station is fully accessible since the vertical and horizontal gaps between the train and platform may still preclude access to those with mobility impairments.

In 2006, the network operator, Transport for London (TfL), embarked on an ambitious upgrade plan that would have seen a quarter of Tube stations fully-accessible by 2010, with a third accessible by 2013 [22]. Priority in accessibility upgrades was given to high-demand stations and, internally, TfL employs a hybrid model based on survey and Oyster data to understand flows and predict changes once improvements are in place. Clearly, the prioritisation of work has to also take into account a multitude of external factors such as legal requirements when doing major works to make stations compliant with the DDA (Disability Discrimination Act), and the scheduling of major external events – such as the Olympic and Paralympic Games – when reaching decisions on new investment.

However, even under normal circumstances TfL would face challenges upgrading access since London's network is one of the world's oldest and most complex: the first line opened to passengers in 1863 [23] and some station platforms are more than 55m below ground-level [24] with other infrastructure passing under, over, and around them. However, the ongoing financial crisis and its impact on public infrastructure investment has placed further constraints on the operator's ability to invest in upgrades; attention has tended to focus on stations where major redevelopment is already occurring (such as at Tottenham Court Road and Victoria). In short, although

[2]This represented roughly 10% of all London stations at that time[20]. As of November 2012, there are 66 accessible stations[21].

TfL is spending heavily to increase accessibility, there are still many places in the network where those with mobility constraints experience substantial difficulties (see Figure 1).

FIGURE 1 ABOUT HERE

Intuitively, we would expect a transit network with constraints on accessibility investment to sacrifice either travel time or interchange frequency. In other words, assuming that an operator hadn't been able to build every station to be accessible right from the start, then the optimal strategy would seem to be either: a) ensuring that some set of accessible interchanges would allow disabled users to access the majority of the network even if they couldn't do so as quickly as non-disabled users; or b) ensuring that some set of high-demand stations were accessible so as to allow more disabled users to reach more destinations quickly even if users of less-trafficked routes experienced much greater difficulty in completing their journey.

In spite of TfL's efforts with respect to strategy ''b', however, the age of London's rail infrastructure still offers wheelchair users the worst of both worlds: disabled users tend to have longer trips *and* more interchanges regardless of journey type. Moreover, wheelchair-accessibility is only *one* type of challenge faced by disabled users of a public transit system, but mobility impairments will be particularly difficult to address in an older network. However, the ageing of Britain's population makes it likely that mobility challenges will become an even bigger issue in the near future, making planning and investment a priority today. Figure 1 illustrates the scope of the problem: a person needing wheelchair-accessible transportation between Royal Victoria and the Whitechapel area (since the station itself will not be accessible until the completion of Crossrail) would face a journey that is roughly 1.8 times longer and entails longer transfers between modes.

Data Description

Fortunately, although a number of cities now employ a variety of smart card technologies, London has had a single system in use for nearly a decade, giving it a great deal of data upon which to base future investment decisions that will impact accessibility. Uptake of the scheme has been extensive, with more than 80% of all journeys on the system being paid for with an

‘Oyster Card’ [25]. Moreover, the system’s design strongly encourages users to validate upon both entry and exit: users with ’pay as you go’ cards are penalised by higher charges for failing to validate at each end, while users with ‘pay monthly’ or other travel permits often need to ‘tap in’ and ‘tap out’ in order to open station or platform gates. There are some exceptions to this ‘rule’, which will be detailed later (see page 19), but the principal issue to note is that users only use their Oyster Card to enter the bus, never to exit.

Regardless, the Oyster charging system means that we have an usual level of insight into the origins and destinations – if not the route choice between them – of users within the system. And TfL has also made available a 5% stratified sample of anonymised Oyster Card activity to developers and researchers free of charge to enable analytical work to be based on a large behavioural sample. Together, these factors mean that London’s public transit network is a particularly attractive environment for this type of research since we have a very good picture of the journey, the number of people making it, and the timing of their trips along this route.

Journey Planning

However, in order to measure the degree to which an urban transportation network is accessible to people with disabilities we also need information regarding the expected travel time and number of interchanges for disabled and non-disabled users. Transport for London’s ‘Journey Planner’[3] software tool is able to take any one of a number of arbitrary locational inputs (postcodes, stations, bus stops, and points-of-interest) and return a journey travel plan that not only includes the route itself – from start to finish, including travel to boarding, and from alighting, points – but also estimates the time required for each stage of the trip. Routes can also be asked to comply with a range of ‘usability’ criteria such as ‘wheelchair accessible’, ‘reduced walking’, ‘fewest changes’, and ‘fastest route’ but is not able to fully account for effects such as congestion on the platform or in lifts to/from the surface that could have a serious impact on, for instance, wheelchair users at peak travel demand times.

For simplicity’s sake we used only the default values: optimization criteria

[3] `http://journeyplanner.tfl.gov.uk`; and see `http://www.tfl.gov.uk/businessandpartners/syndication/default.aspx` for the Application Programming Interface (API) sign-up form.

(fastest journey); maximum number of interchanges (9); maximum 'walk time' (40 minutes); and walking speed (normal). For each possible journey within the set of trips that we considered, we queried the Journey Planner several times while varying both the wheelchair-accessible constraint and time of departure in order to develop a picture of the average travel time involved for disabled and non-disabled users. We should note that the 'travel time' means actual time spent travelling between the point of origin and destination (e.g. it includes walking to the bus stop or station) but that it naturally does not include any initial waiting time (e.g. waiting at home for 10 minutes *before* leaving to catch the bus) induced by our stochastic querying process.

FIGURE 2 ABOUT HERE

Oyster Card Usage

As mentioned above, the publicly accessible Oyster Card data set provides a 5% sample of all journeys performed during one week in November of 2009 on all modes that accepted Oyster Cards for payment. The data is anonymised so it is not possible to identify a traveller from the released data. For the majority of rail stations – except parts of the DLR and Overground network – Oyster Cards must normally be presented at the start and end of a journey so that the gates open and, if applicable, the correct, zone-based fair can be deducted[4]. For bus and tram, users are only required to validate their card upon boarding the vehicle, and so the destination of the passenger is not known.

Technically, we could skip the Journey Planner entirely and use the Oyster data alone to derive travel time from the period between entry and exit validations. However, it is impossible to determine the full range of real-world factors affecting the derived values (e.g. one-off delays, temporary closures, upgrade work, etc); moreover, the data does not provide us with definitive route choices within the Tube network (just entry and exit stations) that

[4]Some Tube and Overground stations leave gates open at quieter times, and a number of National Rail and Docklands Light Rail stations are entirely un-gated

might enable us to make sense of the range of derived values. Consequently, we use the real departure times for journeys, but take the rest of our inputs from the Journey Planner since it offers a better measure of expected travel time and it enables us to gauge the duration of accessible travel accurately.

Data Analysis

For our purposes it is non-sensical to use existing activity by disabled users as an input for the upgrade model: since they can't use a non-accessible station – and so present a kind of 'truncated' set of origins and destinations – we have no direct way of determining the latent local demand for increased access. Consequently, we have based our approach on the assumption that wheelchair accessibility needs are normally distributed across the population. The data driving this assumption are considered in greater detail in the *Supplementary Online Material*, but as a first approximation it is nonetheless reasonable assume that the local demand for access is commensurate with the population boarding and existing a particular station. Furthermore, since the buses are already accessible only non-bus travel was included in this first study, though obviously the inability to use a rail station may have knock-on effect in terms of more bus interchanges.

Regardless, we can begin to understand the impact of wheelchair-only mobility on public transit journeys by examining the difference between unconstrained and constrained journeys. Table 1 is generated by dividing the accessible journey time for every trip in the Oyster data set by the corresponding non-accessible travel time. This gives us a sense of the additional travel incurred by disabled users, and Table 1 indicates that 50% of users pay a nearly 50% additional total travel time 'penalty' if we require the trip to be wheelchair-accessible.

TABLE 1 ABOUT HERE

Since on-board travel time is effectively the same for wheelchair and non-wheelchair travellers once the user in on a vehicle, we can focus on interchange and transfer impacts: although transfers are, on average, 1.11 times longer for wheelchair users the effect is severe for the bottom 10% of travellers; while for interchanges the effect is more pronounced from the 75$^{\text{th}}$ percentile. These results can be explained by the fact – noted in the single example presented in Figure 1 – that wheelchair travel typically entails a higher than average number of interchanges *and* longer transfers between modes. Overall, the cumulative distribution of transfer and interchange indexes follows a power law, with the wheelchair accessibility constraint having a greater impact on the real-world model.

We also wanted to see if any of these indexes were inter-related: Figure 3 compares the accessibility indexes (wheelchair-constrained duration / unconstrained duration) for each – we here bring back total travel time – metric. Values greater than 1 along the x-axis indicate that wheelchair-accessible travel is slower than unconstrained travel according to the metric mapped. Similarly, values greater than 1 on the y-axis indicate that the second metric is also tracking slower travel for wheelchair users. The cases in which both the indexes are equals to 1 (i.e. those in which there is no difference between constrained and unconstrained travel) are respectively: (a) 4.21%; (b) 5.35%; (c) 5.08%.

FIGURE 3 ABOUT HERE

Rather unexpectedly, there are a small number of cases where wheelchair-constrained travel appears to produce an index value ≤ 1 on both axes. However, this appears to be a statistical artefact of the Journey Planner travel time derivation process rather than the identification of unusual cases where wheelchair users are actually able to reach their destinations more quickly. Figures 3a and 3c emphasise that in all but a vanishingly small number of cases constrained travel will be longer than unconstrained travel; however, given what we noted above regarding the tradeoff that we might expect in an ideal, but constrained, transport system between travel time and interchanges for disabled users, it is worth noting that it is not *only* that total travel time is longer, but that we can now be certain that in most cases it involves longer and more complex interchanges and transfers between modes as well (the top-right quadrant in Figures 3a and 3c).

It is, of course, unlikely that mobility-constrained travellers will normally experience *shorter* overall travel times than those without any such constraints, but the three plots in Figure 3 do suggest that interchanges are particularly important and are linked to increases in the transfer time index. Taking again the notion of some 'ideal' but accessibility constrained transit system, we would expect – and want – to see the majority of values falling in the upper-left or lower-right quadrants, implying an ability for users to reach some set of key network nodes in the same time as unconstrained users, and the rest of nodes with fewer transfers even if the total travel time is greater. Collectively, what these figures and tables suggest is that a targeted set of accessibility upgrades will have a much greater benefit for wheelchair users than would be possible if travel were distributed more evenly across the system or if a clear set of trade-offs were already in place.

Spatial & Modal Effects

Since transit systems are inherently spatial, we also need to examine whether the impact on wheelchair-accessible travel time is evenly distributed across the network. Figure 4 shows the geographical distribution of the mean total travel time index values for all station-to-station journeys within metropolitan London. Black indicates little or no difference between accessible and wheelchair-constrained travel, and orange-to-yellow indicate a severe impact. Bus-only travel does not need to be factored into this analysis since the more accessible nature of bus travel should mean that there are minimal differences between the two types of journeys as long as we don't expect a differential impact on transfers between buses.

FIGURE 4 ABOUT HERE

Interestingly, the results do not show a strong differentiation between core and periphery. The age of the infrastructure can be indirectly gauged from the two areas of darker – more accessible – stations in the East and South. The highly accessible track across the bottom of the London's transit system corresponds to the Tramlink service which, as a relatively new system only rolled out in 2000, was designed from the ground up to be fully accessible. Similarly, the DLR in East London also performs much better in terms of the difference between accessible and non-accessible journeys; however, because the Central line – which has comparatively less accessible stations – is the principal connection point for the DLR it has weaker connectivity overall than the Tramlink. In contrast to both of these, several of the stations without step free access towards the edges of the system are particularly old: Leyton, in the East, was opened in 1868 while Moor Park (in the Northwest) dates to 1887.

We also examined how changes to the suggested routing for wheelchair users in terms of mode and transfers played out across all trips extracted from the Oyster Card data set. Table 2 should be read as follows: the left half of the Table (where $-3 \leq \text{Tube} \leq -1$) indicates that adding the wheelchair constraint resulted in a given journey traversing fewer rail segments (where a segment involves no interchanges or transfers) on the Underground, while the right half would represent an increase; similarly, the upper half of the Table indicates that a wheelchair accessible journey traversed fewer bus segments, while the lower half indicates more. The centre of the table (at 0/0) indicates no change. Results in the upper-left and lower-right arise because the addition of a wheelchair constraint could, for instance, route a passenger along one bus route instead of several Tube segments, or cause the passenger to take a much more circuitous route that involves more of *both* modes.

TABLE 2 ABOUT HERE

Consequently, we should read Table 2 to indicate that only 19.3% of journeys would entail no changes of route for the traveller with a major mobility constraint. Nearly 60% of the revised routes entail using at least one less Tube segment, but this change is more than compensated for by the 73% of journeys that require one or more additional bus segments (which will also tend to increase the length and number of associated transfers between buses or between bus and Tube). Unsurprisingly, there are very few journeys that seem to involve fewer transfers on one or both modes, and the numbers in the bottom-right quadrant suggest that a significant minority of journeys are becoming much, much more complex.

TABLE 3 ABOUT HERE

If there are more intermodal changes, then there are also like to be more transfers in which the user is required to walk or roll themselves from one station or stop to another. At times, the transfers can be substantial, involving a journey of several minutes along busy sidewalks. We show here in Table

3 only the results for transfers against bus segments (the comparison for the Tube is available in the Supplementary Online Material as Table 7). What should be noted here is that an increase in bus segments traversed caused by the accessibility constraint is associated with an increase in the number of transfers between stops in just 18% of cases (19% for rail). The reason this number is not higher is that an interchange between two bus routes or between bus and rail may not involve a substantial transfer at all.

When we put all of the contextual information developed in Tables 1 through 3, and Figures 3 and 4 a consistent picture begins to emerge: from the standpoint of wheelchair users, the Underground is the primary mobility challenge, adding both to travel time *and* to complex or frequent interchanges involving substantial transfer distances. Bus travel may involve additional segments, but not corresponding increases in transfers, and the DLR, Tram, and Overground are already substantially – or even wholly – more accessible to wheelchair users. So the prevalence of Tube-travel within real-world O/D flows is critical to understanding where infrastructure investment might be most effectively directed and, accordingly, this is where we will focus the remainder of our analysis.

Methodology

The Journey Planner enables us to measure the accessibility of different stations and points around London, but it does not enable us to evaluate the number of journeys impacted by the presence or absence of wheelchair accessibility at a particular station. So as discussed above, we now need to examine the Tube network in more detail using actual O/D data from the Oyster Card model. In this section we will show how network science can suggest the stations that, once improved, will provide the greatest benefit for people with reduced mobility.

This is not, however, a trivial network analysis: the Underground is composed of 11 lines connecting some 270 stations, some of which use shared platforms for different lines, while in other cases lines at a station may be separated by hundreds of meters (e.g. Bank/Monument). Moreover, determining access can be difficult: some are accessible interchanges only (the platforms are not reachable), some are accessible in only one direction, and some have a mix of accessible and non-accessible platforms! If we ignored this fact, then we would lose the awareness that there are several 'invalid' interchanges for disabled users and so we treat each 'station' as a couple: *(station* $\cap$ *line)*.

Our methodology can be summarised as follows:

1. **Filtering trips.**
   We first analyzed the data generated by travellers without a wheelchair accessibility requirement. For each of our 100,000 trips, we considered only those suggesting Tube usage since our aim is now to consider the impact of changes to the Tube alone. The resulting dataset consists of 83,271 trips.
2. **Computing statistics.**
   For each trip obtained in the previous step, we computed a set of statistics (summarised in Table 4) that would enable us to compare travel time and interchange results for accessible, non-accessible, and upgraded-to-become-accessible trips (i.e. what the travel time would become after our proposed upgrade or set of upgrades).
3. **Ranking stations.**
   Using the statistics computed in the previous step, we could select for different optimization criteria: total travel time, transfer time, number of trips and number of interchanges.

TABLE 4 ABOUT HERE

Table 4 offers a set of illustrative statistics used to compare the accessible and wheelchair-constrained journeys. Trip #1 begins at station A and terminates at Y, with interchanges at B and M. The two interchange stations are not, however, accessible for wheelchair users so the Journey Planner suggests a different route entirely (a combination of buses instead). Comparing the travel and transfer times, as well as the number of interchanges indicates that upgrading B and M would save each wheelchair user 24 minutes of travel time and 12 minutes of transfer time, while requiring one less interchange. Similar values were computed for *every* trip with the results weighted by the number of travellers making each journey.

FIGURE 5 ABOUT HERE

Although a follow-up analysis could consider all of the derived metrics, we focus here only on the potential impacts on total travel time. In this case, we simply summed up the time saved by the upgrading of each station or combination of stations in the network. Figure 5 summarises this process: in this schema each node shows the benefits to wheelchair users that the corresponding stop (or combination of stops) would bring if upgraded. For example, if *(Victoria ∩ District)* were made accessible, then according to our data people with reduced mobility would save a total of 6,037 minutes with an average of 15.84 minutes per trip for a net benefit of 0.32% with respect to the total time that could be saved if all stations were made accessible.

If both *(Victoria ∩ District)* and *(Farringdon ∩ Hammersmith & City)* were made accessible, the additional benefit is simply the sum of single benefits. But note that, if *(Victoria ∩ District)*, *(Farringdon ∩ Hammersmith & City)* and *(Green Park ∩ Piccadilly)* are all made accessible[5], then the additional travel time benefit is greater than the sum of the single stations benefits or even the pairwise benefits. This type of result can happen because there are some 33 trips that use all three stations, producing an additional net benefit of 301 minutes!

Results

The previous section provided an illustrative example of how the potential benefits accruing to wheelchair users from a station upgrade could be calculated. In the current financial context, however, TfL is unlikely to be able to upgrade a significant number of stations and so we now need to assess which station(s) produces the greatest benefit. If we optimise only for total travel time (a reasonable step, since this is the criterion often used in transport investment), then what are the highest-impact choices?

FIGURE 6 ABOUT HERE

For one station alone, the solution is fairly trivial: Figure 6 shows the frequency distribution of time saved as a percentage of total travel time that

[5] We should note that Farringdon and Green Park *are* now accessible, but were not at the time we conducted our research.

could be saved if all stops were to be made accessible. Clearly, the majority of station upgrades provide only a marginal improvement, but some small number of stations provide a substantial gain to wheelchair users. In this case, the answer is the Hammersmith & City platforms at Farringdon, followed by the District line at Victoria station. Rather less expected, however, are the proposed upgrades at Balham, Parsons Green and Hendon Central (see Figure 7a) – these stations are less central and are not major interchange points. The explanation lies in the enormous changes to journey times: wheelchair users who might prefer to use, say, Hendon Central are currently required to travel by bus instead – and so are subject to the vagaries of their schedules, congestion, and routing – in order to connect with an accessible station, and so upgrade work yields a large number of minutes saved.

The fact that our analysis selects these stations suggests that the cumulative loading effects can produce some surprising results. To understand why, recall that the results are based on 100,000 trips made by users without an accessibility constraint. From this large number of trips we excluded those that were *already* fully accessible in terms of entry, interchange, and exit points. Logically, what remains are trips where one or more points are not accessible to wheelchair users. So in the case of Figure 7a we have 563 trips where the lack of full accessibility at A is the only thing keeping wheelchair users from making the journey. There may well be many other trips for which the upgrading of A is necessary, but it is not sufficient since there is at least one *other* station that also needs to be upgraded for the journey to become fully accessible.

FIGURE 7 ABOUT HERE

Figure 7a more formally presents the results of the ranking methodology using a single station. However, as we increase the number of possible station upgrades beyond one stop, the picture becomes more complex and the summary view provided in Figure 6 is no longer sufficient to select stations. So Figure 7b shows the top five solutions if we could upgrade two stops instead of just one. Note first that solution A,B is the sum of the first two solutions in Figure 7a, but that the optimal solution here is $\{B,F\}$, where the braces around B and F mean that this solution is driven predominantly by trips that use these two stops in tandem.

TABLE 5 ABOUT HERE

Although $\{B,F\}$ is affected primarily by the set of journeys using these two stations sequentially as interchanges or termini, in order to compute the optimal solution we do still have to take into account not only trips that traverse the available station pairs, but also those that use just one of these stations on its own. In other words, there are many other trips that will also benefit from either of these stations being upgraded. Similar considerations affect the optimal solutions for three stops (see Figure 7c) or more (see Table 5). Although the solutions clearly become increasingly complex and computationally expensive as the number of potential upgrades increases, we are still dealing with a fairly tractable network.

We also compared the results of our ranking methodology with a those of a simpler approach that considers the busiest stations based on the number of entries and exits. Among these stations, we considered only the ones having at least one inaccessible line. For example, we did not take into consideration London Bridge (ranked 3rd) because both the Jubilee and Northern lines at that station are fully accessible. Since this methodology does not take into account the output of the Journey Planner we called this methodology a 'static ranking'. We could then rank all the stations according to the time saved if they were made accessible. Table 6 shows the results of this more naïve approach compared to our original results.

TABLE 6 ABOUT HERE

The left part of Table 6 shows the output of the static analysis, highlighting the busiest stations and their respectively ranking according to the number of entries and exits (completely accessible stations are here disregarded). The right part of the table shows how the same stations (taking into consideration all their respectively not accessible lines) are ranked in our network analysis. In particular, we found 101 pairs of not accessible *(station* $\cap$ *line)* for which making them accessible would result in a non-zero travel time saved for people with disabilities. Most of the stations prioritised in the static analysis are not even listed in the dynamic one, and this happens because it is obviously – as we have demonstrated – not just the start and the end points that need to be upgraded to make the entire trip accessible. These results highlight the need to use the Journey Planner in conjunction with real travel demand to prioritise upgrade work.

FIGURE 8 ABOUT HERE

In Figure 8 we compare the impact of selecting only for travel time with that of selecting other optimisation criteria. So here we can see the minutes saved by optimising for total travel time, with the minutes that could be saved if we used other ranking methods to optimise between one and five stations. The choice of three alternate rankings is not meant to be complete, but it gives a sense of the competing rankings that could be easily computed using the available data. In Figure 8, optimisation on the number of affected trips produces similar results to optimisation on travel time, while optimisation on interchanges and transfer time seems to produce more modest impacts.

Discussion

In this paper we have introduced a general methodology, based on network and spatio-temporal analysis, for measuring the performance of the network in terms of its accessibility for people with disabilities. In principle, the method can be applied to any transportation network for which it is possible to assess the volume and routing of passengers over time, and we feel that this approach can augment existing approaches – such as those employed in London – based primarily on survey data or hybrid O/D and smart card analysis. Our approach focuses on identifying the greatest barriers faced by wheelchair users in the system and, by ranking stations in terms of their impact on accessibility, suggesting the best solutions to minimise the difference between normal and wheelchair-constrained travel. By offering a prioritisation schema to network operators the approach also respects the fact that the time and money budgets are finite.

Taking public transportation in London as a case study, we found that a large proportion of trips can be significantly affected when a system is unable to provide fully-accessible stations, stops, and vehicles. Indeed, upgrades to the rail network that increase accessibility for disabled users by reducing the need for difficult multi-modal interchanges could even benefit other users by reducing the time needed for safe boarding and alighting at bus stops. However, while TfL has taken many creative, low-cost approaches to improving access – such as the raising of part of a platform to align it with the train's doors and allow wheelchair users to board – there remains an enormous amount of expensive work to be done to allow step-free access from street-to-platform or even to another line at an interchange! Our work therefore focussed on the $station \cap line$ 2-tuple as the natural unit of analysis (though one could also easily make the case for a $station \cap line \cap platform$ 3-tuple) and sought to identify the units whose upgrade would deliver the greatest benefits using a single optimisation metric.

We recognise, of course, that wheelchair-constraints represent only one type of disability amongst many – visual, auditory, and mobility – but we believe that such techniques have implications for future research in this area. In particular, an ageing population is likely to become increasingly dependent on accessible public transport, and the network operator will have to balance the need for improvements to address this group's needs with the potential cost and scope of the desired upgrades. The approach elaborated here can also form part of a discussion around the balance between upgrades and dedicated services such as Dial-A-Ride, which attempt to create point-to-point services on an as-needed basis. This issue here is that dedicated paratransit appears to be more costly – in terms of both time and money – on a per-user basis[26] and to offer more tightly circumscribed benefits (e.g. it does not serve all travellers with mobility constraints, must be pre-booked (often as much as a day in advance), and can require users to wait up to 30 minutes for the service[27]).

This is, however, only an exploratory analysis and we should note that our results may have been affected by bias introduced at several points in the research, not least of which is the fact that the data comes from different periods of time: the Oyster data, as noted earlier, dates from November 2009, the Journey Planner results date from 2012 and are provided by TfL in real-time (so they may be affected by disruption), and the accessibility situation is current only as of June 2012. We also treated the Journey Planner as a kind of 'black box' from which to derive the most likely path that a traveler would follow between points A and B. We believe that this approach is reasonable for wheelchair users since the mobility constraints are quite severe and are fairly well known by the operator.

However, frequent commuters – disabled or not – may well opt for alternate, less obvious routes that are faster or offer other benefits (a seat from start to end, for instance). Indeed, many disabled users face a host of challenging issues navigating even a system that is wholly accessible: crowding on platforms causing safety issues, the reliability of the accessibility infrastructure, appropriate signage to aid wayfinding, and the existence of 'street furniture' or other impediments, to name only the most obvious. A more subtle issue is that an individual's own experience of the system may throw up accessibility issues, such as the gap between platform and train, that do not accord perfectly with the Planner's 'knowledge' of the system and implying that some expert knowledge is not yet fully captured by our methodology.

So there is some question as to how accurate the Journey Planner is as a tool for modelling global routing preferences, and we also discovered some rare instances in which the Planner returned incorrect travel times or even failed to return a trip with the same origin or destination. Across several hundred thousand iterations, these errors had comparatively little influence: their cumulative effect was less than 3% on the resulting aggregate analyses. Given these issues, there is a obvious need for expert input from the community of mobility-constrained users (and potential users) to validate and feed back on these findings, and we would suggest that this is an important area for further research; however, by narrowing the range of options to consider we think that this approach makes a valuable contribution to long-range planning by operators.

Combining the Journey Planner with real-world usage from the Oyster Card data set introduces a second source of bias: since location data is not available for bus trips, the resulting O/D matrices are limited to the rail systems alone. We attempted to compensate for this by extracting time- and distance-based distributions from the travel data (including bus trips in the temporal distribution), and using them to simulate other trips from random locations in the city. The generated trips have random origins and destinations, but their length and duration reflect the known distribution of Oyster Card activity. While imperfect, the resulting matrix covers the whole city, which is important for this type of work. Fortunately, this limitation is rapidly changing and we expect the rollout of the 'iBus' countdown service to enable TfL to geolocate boarding activity on buses as well (though exits will still need to be inferred since users do not have to 'tap out' of buses).

As stated near the start of this work, we do not believe that the use of Oyster card data alone represents a major problem: more than 80% of trips within London are paid for using these cards [25], and the introduction of ITSO cards across the rest of Britain's rail system should increase this number further still. Furthermore, a comparison of Retail and Freedom Card usage (see Figure 10 in the Supplementary Online Material) did not indicate a major difference between the travel patterns of regular users and those who had registered for disabled cards.

The one concern with the Oyster data set is that the use of untraceable magnetic tickets is *not* randomly distributed across the network since their usage is linked to bundled National Rail and tourist tickets purchased outside London and commonly used at the 'gateway' stations of Liverpool Street, Victoria, Paddington, Waterloo, and Charing Cross. As well, a portion of travellers regularly commuting to London via National Rail will also use magnetic tickets and so their trips will also not be visible in the Oyster data. Accordingly there will be undercounts in a very particular set of circumstances – and we may also be underestimating demand at particular times because disabled users may avoid rush hour travel – but we feel that this is a worthwhile price to pay for the overall comprehensiveness of the data and that TfL could seek to address this issue with more targeted and, consequently, less costly surveys.

London's ageing infrastructure creates an especially challenging environment in which to plan major works; in some cases, a planned upgrade may be discovered to be structurally unfeasible only after substantive work has already begun (see, for example, the problems detailed in [28]). However, the results from this type of analysis, especially if paired with additional, individualised support for travellers with reduced mobility (see, for example, *AccessMyNYC*[6]), could be used to deliver increased service levels to users through enhanced connectivity, information, and investment, helping the operator to maximise the return on its upgrade investment. We are planning to conduct further studies with local authorities to validate our approach and hope to see real benefits for disabled users in the future.

Acknowledgments

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[6]See `http://www-03.ibm.com/able/news/Accessmynyc.html`.

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References

[1] D. Balcan, B. Gonçalves, H. Hu, J. J. Ramasco, V. Colizza, A. Vespignani, Modeling the spatial spread of infectious diseases: The global epidemic and mobility computational model, Journal Computer Science 1 (2010) 132–145.

[2] Z. Dezső, A.-L. Barabási, Halting viruses in scale-free networks, Physical Review E 65 (2002) 055103.

[3] R. Trasarti, F. Pinelli, M. Nanni, F. Giannotti, Mining mobility user profiles for car pooling, Proceedings of the 17th ACM SIGKDD international conference on Knowledge discovery and data mining, KDD '11 (2011) 1190 – 1198.

[4] J. Reades, F. Calabrese, A. Sevtsuk, C. Ratti, Cellular census: Explorations in urban data collection, IEEE Pervasive Computing 6 (2007) 30–38.

[5] F. Calabrese, F. Pereira, G. DiLorenzo, L. Liu, C. Ratti, The geography of taste: analyzing cell-phone mobility and social events, Proceedings of the 8th International Conference on Pervasive Computing, Pervasive'10 (2010) 22–37.

[6] M. Bielli, M. Caramia, P. Carotenuto, Genetic algorithms in bus network optimization, Transportation Research Part C: Emerging Technologies 10 (2002) 19 – 34.

[7] F. Pinelli, A. Hou, F. Calabrese, M. Nanni, C. Zegras, C. Ratti, Space and time-dependant bus accessibility: a case study in Rome, Proceedings of the 12th International IEEE Conference on Intelligent Transportation Systems, ITSC'09 (2009) 1–6.

[8] Y. Zheng, Y. Liu, J. Yuan, X. Xie, Urban computing with taxicabs, Proceeding of the 13th International Conference on Ubiquitous Computing, UbiComp'11 (2011) 89–98.

[9] C. Roth, S. M. Kang, M. Batty, M. Barthelemy, Structure of urban movements: Polycentric activity and entangled hierarchical flows, PLoS ONE 6 (2011) e15923.

[10] L. Liu, A. Hou, A. Biderman, C. Ratti, J. Chen, Understanding individual and collective mobility patterns from smart card records: A case study in Shenzhen, Proceeding of the 12th International IEEE Conference on Intelligent Transportation Systems, ITSC'09 (2009) 1–6.

[11] N. Lathia, J. Froehlich, L. Capra, Mining public transport usage for personalised intelligent transport systems, Proceeding of the 10th IEEE International Conference on Data Mining, ICDM'10 (2010) 887–892.

[12] N. Lathia, L. Capra, How smart is your smartcard?: Measuring travel behaviours, perceptions, and incentives, Proceeding of the 13th International Conference on Ubiquitous Computing, UbiComp'11 (2011) 291–300.

[13] N. Lathia, L. Capra, Mining mobility data to minimise travellers' spending on public transport, Proceedings of the 17th ACM SIGKDD international conference on Knowledge discovery and data mining, KDD'11 (2011) 1181–1189.

[14] P. Kasemsuppakorn, H. A. Karimi, Personalised routing for wheelchair navigation, Journal on Location Based Services 3 (2009) 24–54.

[15] D. Karimanzira, P. Otto, J. Wernstedt, Application of machine learning methods to route planning and navigation for disabled people, Proceedings of the 25th IASTED international conference on Modeling, indentification, and control, MIC'06 (2006) 366–371.

[16] J. Svensson, Accessibility in the urban environmnet for citizens with impairments: using gis to map and measure accessibility in Swedish cities, Proceeding of the 59th Annual Conference of the International Communication Association, ICA'09 (2009).

[17] A. Steinfeld, R. Aziz, L. V. Dehsen, S. Park, J. Maisel, E. Steinfeld, The value and acceptance of citizen science to promote transit accessibility, Journal of Technology and Disability 22 (2010) 73–81.

[18] M. J. F. Committee on Disability in America, e. Alan Jette, The Future of Disability in America, The National Academies Press, 2007.

[19] P. Tisato, Travel Affordability in Adelaide for People with Disabilities, Papers 96.4, South Australian Centre for Economic Studies-, 1996.

[20] Transport for London, Step-free access, 2011.

[21] Transport for London, Farringdon becomes the 66th step-free tube station, 2012.

[22] Transport for London, Transport for London News, 2006.

[23] London Transport Museum, World's first underground, 2012.

[24] Transport for London, Key facts, 2012.

[25] Transport for London, Oyster factsheet, 2012.

[26] BBC, London's Dial-a-ride for disabled 'not cost-efficient', 2010.

[27] Transport for London, Your guide to Dial-a-Ride, 2012.

[28] R. Bloomfield, TfL wastes 64 million abandoning disabled access plans on the Tube, London Evening Standard (2010).

[29] Transport for London, Transport for London Developers' Area, 2011.

[30] Transport for London, King's cross st. pancras tube station is step-free with 10 new lifts, 2010.

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2. Supplementary Online Material

Comparison with Null Models

Although not strictly necessary, since no real-world transit system would have truly random behaviour, we thought it would be useful to briefly compare how actual activity driven by human behavioural patterns differs from that of an artificial null model in which behaviour is entirely random. We generated a synthetic data set in which 100,000 trips were randomly distributed across space and time, and compared it to a model that is based on real-world usage.

FIGURE 9 ABOUT HERE

To ensure that the entire metro region was appropriately covered by our analysis, we created a raster grid with square cells of 500m on a side and grouped O/D information accordingly – this gave us complete coverage in the Random data set, but not in the Oyster Card data. For the random flows we also required that the start and end point be at least 1,000m apart, and from the Oyster Data only non-bus trips were used.

Figure 9a shows the enormous peak in departure times that exist in a real-world system: the morning and evening rush hour peak at more than 3 times that of the random distribution. And Figure 9b highlights the fact that the bulk of daily trips are very much less than the nearly system-spanning 30km seen in a fully random distribution. The results highlight structural differences of considerable importance and emphasise that any solutions based on randomised flows are analytically irrelevant.

Transfer Impacts of Wheelchair Constraints

Table 7 shows that the accessibility constraint is associated with a decrease in Tube segments (i.e. distinct Tube lines) traversed and only a fairly modest increase in transfers. Given the results obtained from Tables 3 and 2 (see pages 42, 41), these results suggest a strong shift from multi-Tube line journeys to trips that involve more bus and inter-bus transfers. The net impact of this change is longer travel times for users, part of which is coming from the slower speed of bus travel, and part of which is coming from time spent changing modes. Again, these findings highlight the beneficial impact that a more fully accessible Underground network could have on wheelchair users.

TABLE 7 ABOUT HERE

Travel Demand Comparisons

FIGURE 10 ABOUT HERE

The anonymized Oyster Card data set provided by TfL (for the related documentation see [29]) combines data coming from several different types of card: *Bus and Tram Pass*, *Freedom Pass (Disabled Users)*, *Freedom Pass (Elderly Users)*, *LUL Travelcard*, *Pay-As-You-Go*, *Staff Pass* and *Retail Pass* (all other users without discounts, valid periods, or limitations). Within this, the activity generated by disabled people is only a small part: of the $2,623,487$ trips in the data set, only 2.8% ($73,260$ trips) are generated by disabled users with a Freedom Pass, and only 0.44% ($11,475$ trips) of those involve the use of Tube stations as starting and ending points. Moreover, the accessibility picture captured in the Oyster extract cannot be synchronised with the Journey Planner: for instance, when the Oyster data was collected in 2009, King's Cross St. Pancras was only partially step-free from street to platform (only the platforms used by the Northern and Victoria lines had been upgraded), but in September 2010 the entire station become fully accessible[30].

To obtain a sense of whether strong spatial biases exist in how disabled users with Freedom Passes use the system, in Figure 10 we compare the percentage of all flows represented by a single O/D pair for Freedom Pass against that of all Retail card users. This metric is derived only for the $551,669$ trips between Tube stations using the following simple formula:

$$\frac{log(^{A}/_{B})}{log(^{C}/_{D})} \tag{1}$$

where A is the number of trips between an origin and destination by Freedom Card users, B represents the total number of trips made by Freedom Card users, C the number of trips between the same origin and destination by users of any other Oyster card, and D is the total number of trips made by all the other card holders.

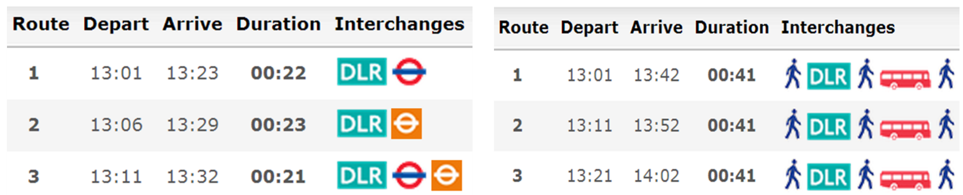
FIGURE 11 ABOUT HERE

We would not expect to find all observations in Figure 10 lying neatly along the reference line since we know already that some parts of the system are inaccessible to wheelchair users; however, the results also indicate that there are no obvious major biases either. Consequently, it seems reasonable to infer – as a starting point for this work – that disabled users are distributed within the general population in such a way as to allow us to use the much larger Retail user volumes as a rough proxy indicator for users who are currently unable to use an inaccessible station.

We also analysed the relationship between the travel time ratio and distance to determine if the wheelchair-constrained travel time is structurally impacted by the distance travelled. The idea is that low distance values might correspond to high values of the total travel time ratio since they would be disproportionately impacted by the increase in interchange and transfer times. Plotting this relationship in Figure 11 suggests that there is *some* truth to this assumption, but that the result is far from predictable. Functionally, this means that we are not dealing with a simple case of upgrading some small number of central stations to enable shorter journeys to be fully accessible; instead, a global perspective is required to identify which stations can be upgraded to offer maximum accessibility at least cost.

Figure 1: **Example of suggested routes from Royal Victoria to Whitechapel** on the 19 Jan 2013 at 13:06 (image taken from http://journeyplanner.tfl.gov.uk).

(a) Without Constraints (b) With Wheelchair-accessible Constraint



Route	Depart	Arrive	Duration	Interchanges
1	13:01	13:23	**00:22**	DLR
2	13:06	13:29	**00:23**	DLR
3	13:11	13:32	**00:21**	DLR

Route	Depart	Arrive	Duration	Interchanges
1	13:01	13:42	**00:41**	DLR
2	13:11	13:52	**00:41**	DLR
3	13:21	14:02	**00:41**	DLR

Figure 2: Core of TfL Network as of November 2012

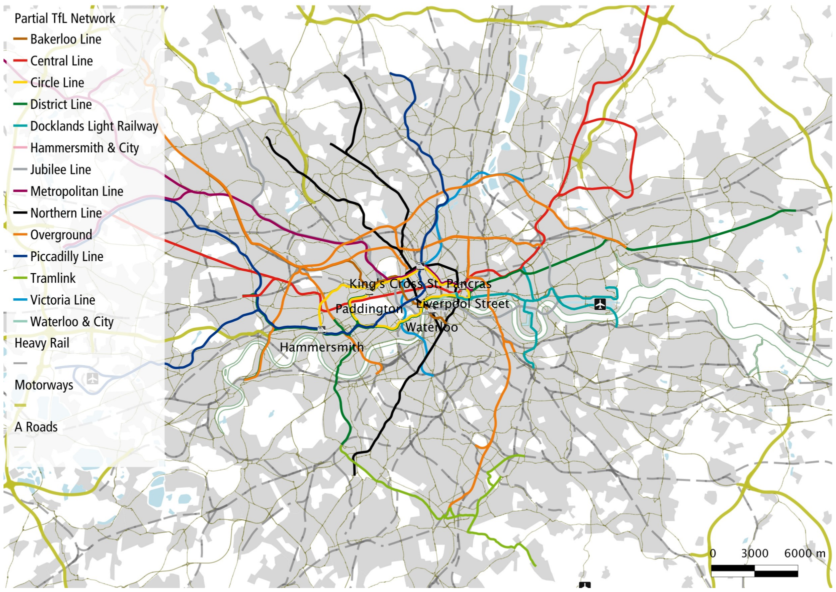


Figure 3: **Comparison of Indexes.** Numbers represent the percentage of trips falling into each of the quadrants (see text). Each plot is divided into four quadrants: the upper-left in which $x < 1$ and $y \geq 1$, the upper-right in which both the variables are greater than 1, and the bottom-right in which $x \geq 1$ and $y < 1$.

(a) Comparison 1 (b) Comparison 2 (c) Comparison 3

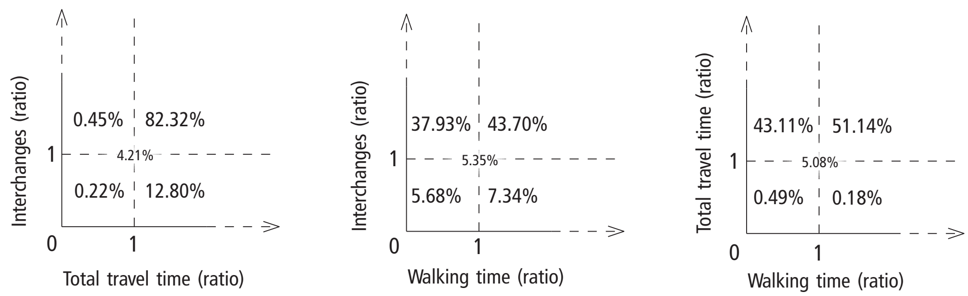


Figure 4: **Spatial distribution of the total travel time index** (mean values) for the Oyster Card model. National Rail lines not shown.

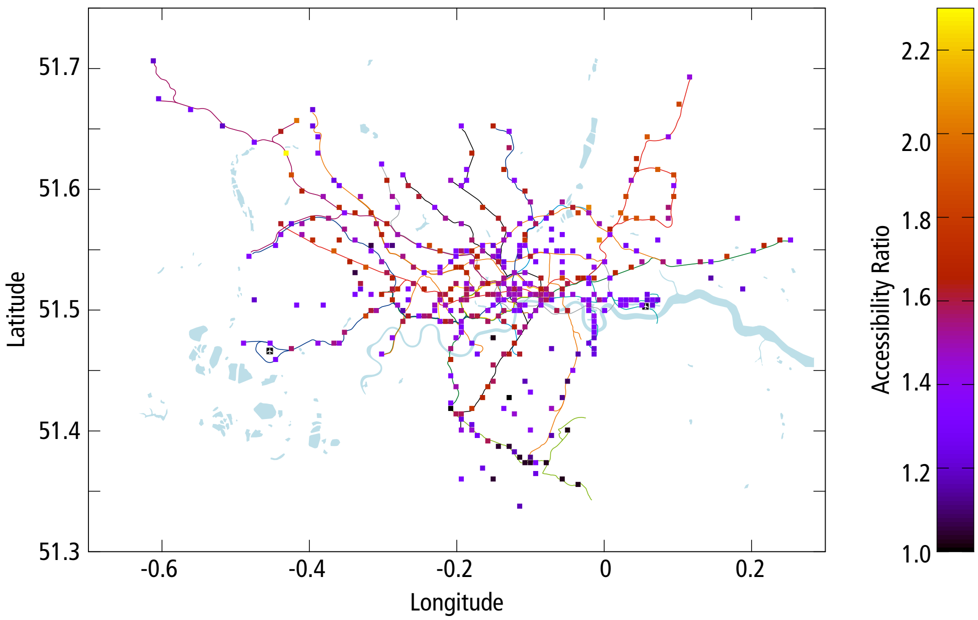


Figure 5: **Part of the tree representing all the possible solutions.** Each node shows the benefits that the corresponding stop (or combination of stops) would bring if made accessible.

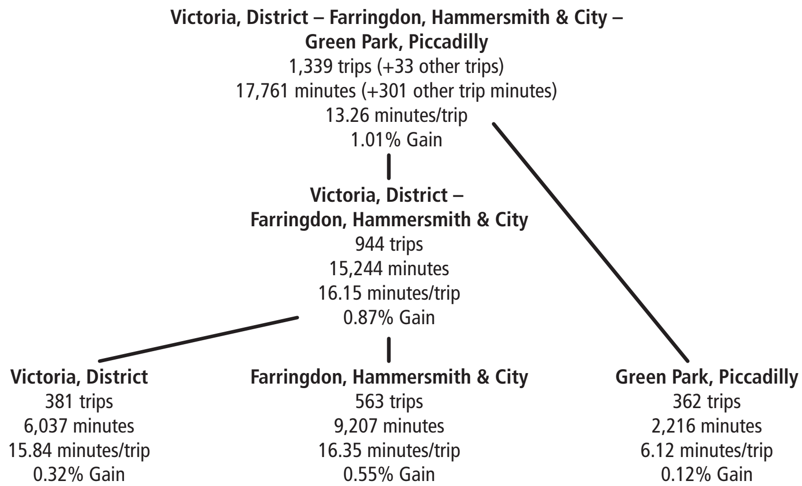


Figure 6: **Number of stations as a function of the percentage of time saved.**

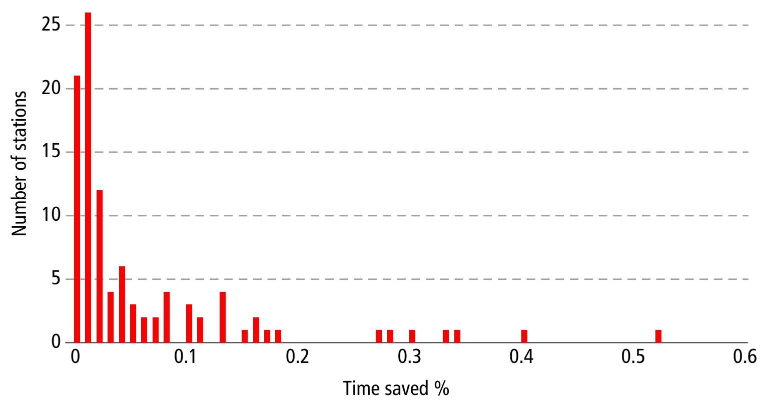
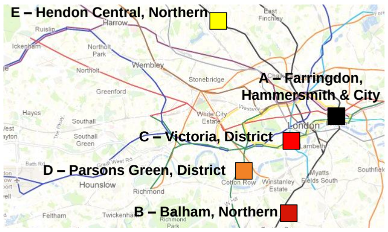


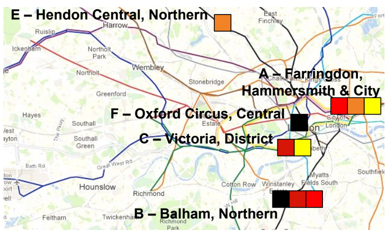
Figure 7: **Ranking Results:** Top 5 solutions for the optimisation of one stop *(a)*, two stops *(b)* and three stops *(c)*

(a) Optimization of one stop



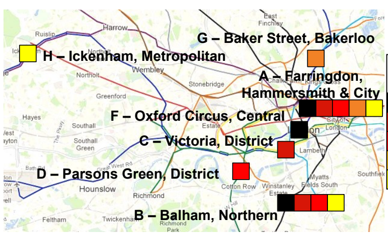
RANKING	STOP-ID	NUMBER OF TRIPS	TOT MINUTES SAVED (min)	AVG TIME SAVED (min/trip)	SAVED %
1	A	563	9207	16.35	0.52
2	B	145	7051	48.63	0.4
3	C	381	6037	15.84	0.34
4	D	321	5752	17.92	0,33
5	E	305	5350	17.54	0,33

(b) Optimization of two stops



RANKING	STOP-ID	NUMBER OF TRIPS	TOT MINUTES SAVED (min)	AVG TIME SAVED (min/trip)	SAVED %
1	{B,F}	533	16590	31.12	0.94
2	{B,C}	588	16502	28.06	0.93
3	A,B	708	16258	22.96	0.92
4	{A,E}	918	16119	17.56	0.91
5	A,C	944	15244	16.15	0.87

(c) Optimization of three stops



RANKING	STOP-ID	NUMBER OF TRIPS	TOT MINUTES SAVED (min)	AVG TIME SAVED (min/trip)	SAVED %
1	{B,F},A	1096	25797	23.54	1.46
2	{B,C},A	1151	25709	22.34	1.46
3	{B,D},A	1055	23453	22.23	1.33
4	{A,G},B	1063	23170	21.8	1.32
5	{B,H},A	888	22922	25.81	1.3

Figure 8: Differences between optimisation criteria.

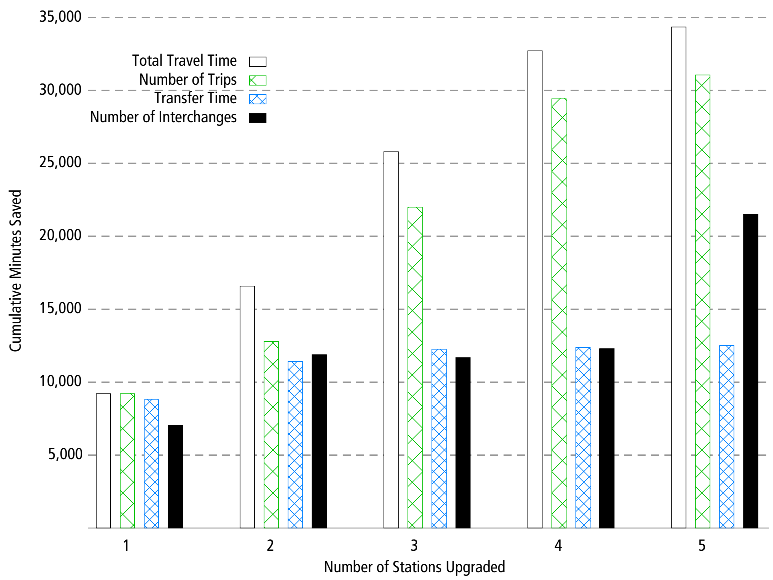
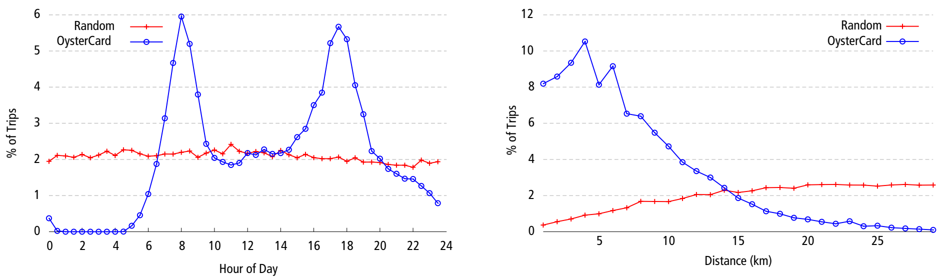


Figure 9: **Temporal and spatial distributions of trips** (color image).

(a) Temporal Distribution

(b) Distance Distribution



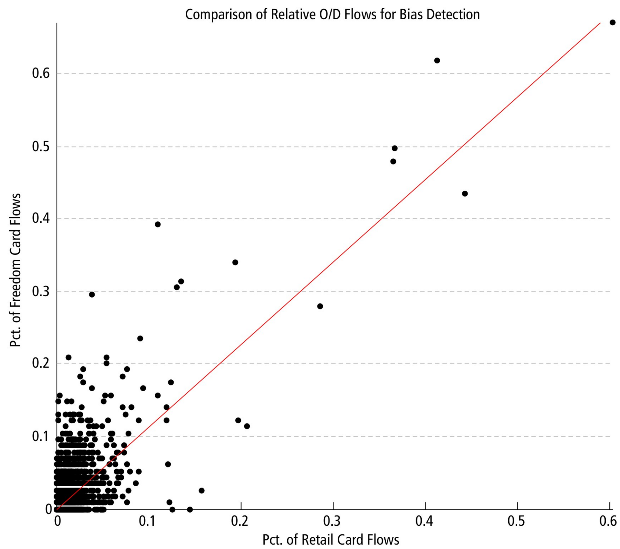


Figure 10: Comparison of Relative O/D Flows for Bias Detection.

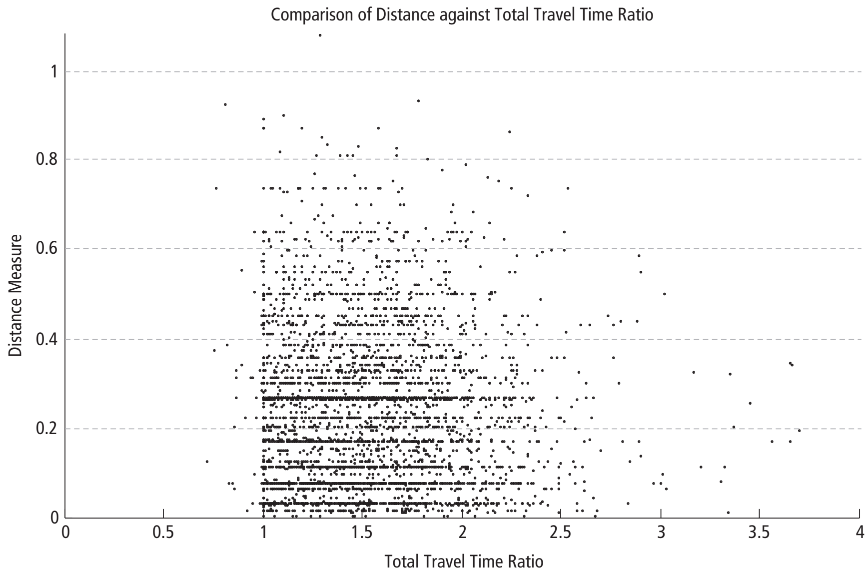


Figure 11: Ratio and distance comparisons.

Percentile	Total	Transfer	Interchange
Mean	1.527	**1.110**	**1.256**
25%	1.246	0.692	1.000
50%	**1.478**	1.000	1.000
75%	**1.750**	1.389	1.500
90%	2.023	1.846	2.000
95%	2.200	2.167	2.333
100%	5.636	7.200	5.000

Table 1: **Percentiles for Accessibility Indexes of Oyster Card Model**: total travel time, transfer time, and number of interchanges.

Bus \ Tube	-3	-2	-1	0	+1	+2	+3	SUM
-3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01
-1	0.00	0.00	0.07	0.27	0.12	0.02	0.00	0.48
0	0.01	0.37	3.54	**19.30**	2.73	0.27	0.01	26.23
+1	0.42	6.51	23.56	10.25	2.59	0.39	0.01	43.73
+2	1.11	6.26	12.02	3.64	1.30	0.13	0.01	24.47
+3	0.41	1.43	1.94	0.52	0.25	0.03	0.00	4.58
SUM	1.95	**14.57**	**41.13**	33.98	6.99	0.85	0.03	

Table 2: **Changes in Segment by Mode**: accessibility-driven effect on the number of rail and bus segments traversed.

Transfer \ Bus	-3	-2	-1	0	+1	+2	+3	SUM
-3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-2	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01
-1	0.00	0.01	0.10	0.51	0.60	0.25	0.03	1.50
0	0.00	0.00	0.35	25.06	36.35	15.51	2.45	**79.72**
+1	0.00	0.00	0.02	0.63	6.60	7.91	1.63	**16.79**
+2	0.00	0.00	0.00	0.02	0.17	0.80	0.44	1.43
+3	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03
SUM	0.00	0.01	0.47	26.22	**43.73**	**24.48**	4.57	

Table 3: **Changes in Transfers**: accessibility-driven effect on the number of transfers against the total number of bus segments traversed.

Trip Id	1
Stops	Station #1, Station #2, Station #3, Station #4
Not-Accessible Stops	Station #2, Station #3
Total Travel Time (min.)	+24
Transfer Time (min.)	+12
Number of Interchanges	+1

Table 4: **Illustrative trip statistics.**

Table 5: **Top 5 solutions for the optimisation of four and five stops**.

Ranking	Stop Ids	Number of Trips	Total Minutes Saved	Average Time Saves (min/trip)	Saved % Saved %
		OPTIMIZE FOUR STOPS			
1	{A,F}, {B,E}	1,451	32,709	22.54	1.86
2	{A,C}, {B,E}	1,506	32,621	21.66	1.85
3	{A,F}, {B,G}	1,288	30,747	23.87	1.75
4	{A,C}, {B,G}	1,343	30,659	22.83	1.74
5	{A,B}, {E,D}	1,410	30,365	22.61	1.72
		OPTIMIZE FIVE STOPS			
1	{A,I},{C,F,L}	1,872	34,351	18.35	1.95
2	{A,I},{D,F,L}	1,798	34,043	18.93	1.93
3	{A,I},{C,D,L}	1,853	33,955	18.32	1.92
4	A,C,B,E,D	1,715	33,397	19.47	1.89
5	A,C,F,B,D	1,720	33,060	19.22	1.88

Station combinations are as follows: A=Farringdon ∩ Hammersmith & City; B=Balham ∩ Northern; C=Victoria ∩ District; D=Parsons Green ∩ District; E=Hendon Central ∩ Northern; F=Oxford Circus ∩ Central; G=Baker Street ∩ Bakerloo; I=Upminster Bridge ∩ District; L=Green Park ∩ Piccadilly

Table 6: **Comparison of the ranking results between the static and our methodology**. In particular, we found 101 pairs of not accessible *(station ∩ line)* for which making them accessible would result in a non-zero travel time saved for people with disabilities.

Station	Entries and exits ranking	Not accessible lines	Our ranking	Minutes saved
Waterloo	1	Bakerloo	> 101	0
		Northern	61	167
		Waterloo & City	> 101	0
Victoria†	2	Circle	> 101	0
		District	3	6037
		Victoria	> 101	0
Liverpool Street	4	Central	> 101	0
		Circle	> 101	0
		Metropolitan	> 101	0
		Hammersmith & City	> 101	0
King's Cross St. Pancras‡	5	Circle	> 101	0
		Metropolitan	66	136
		Piccadilly	> 101	0
Oxford Circus	6	Bakerloo	> 101	0
		Central	6	5013
		Victoria	> 101	0
Stratford‡	8	Central	> 101	0
Bond Street	9	Central	> 101	0
		Jubilee	> 101	0
Piccadilly Circus	10	Bakerloo	> 101	0
		Piccadilly	> 101	0
Charing Cross	11	Bakerloo	45	395
		Northern	> 101	0
Euston	12	Northern	75	100
		Victoria	> 101	0
Leicester Square	13	Northern	> 101	0
		Piccadilly	> 101	0
Vauxhall	14	Victoria	> 101	

†Upgrade works at Victoria Station are scheduled to finish in 2018.

‡King's Cross St. Pancras and Stratford have now been upgraded.

Transfer \ Tube	-3	-2	-1	0	+1	+2	+3	SUM
-3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-2	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.02
-1	0.03	0.40	0.64	0.29	0.12	0.03	0.00	1.51
0	1.46	11.35	33.40	28.22	4.91	0.53	0.02	**79.90**
+1	0.49	2.77	6.70	5.04	1.68	0.27	0.01	**16.95**
+2	0.03	0.22	0.48	0.49	0.29	0.02	0.00	1.53
+3	0.00	0.01	0.02	0.01	0.00	0.00	0.00	0.05
SUM	2.00	**14.77**	**41.25**	34.05	7.00	0.85	0.03	

Table 7: **Net Change in Transfers**: number of Transfers vs. number of Rail segments.